

Quay crane assignment in container terminals using a genetic algorithm

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ABSTRACT

Ports are essential for international trade, connecting production areas to consumer markets. However, port operations often face delays, disrupting supply chains and increasing transit times. To address this, mathematical modeling, particularly through genetic algorithms, offers a solution for optimizing processes like container unloading. This paper presents a model predicting and optimizing unloading times by considering factors such as crane types, schedules, and environmental conditions. Focusing on the Casablanca port, the model addresses scheduling for two gantry and two mobile cranes, treating each bay as a unique task handled by one crane type to avoid conflicts. Using genetic algorithms, the goal is to create efficient schedules that minimize waiting times and maximize crane utilization. The expected outcome is a detailed timetable enabling effective gantry crane use or simultaneous multi-crane operations, enhancing unloading efficiency. This approach can be adapted to other ports with similar challenges, highlighting the model's broader applicability.

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1. INTRODUCTION

Streamlining import, export, and international transit procedures is one of the primary suggestions of the Trade Facilitation Agreement (TFA) [1], which was drafted by the World Trade Organization (WTO) during the 9th Ministerial Conference in Bali in November 2013. The TFA encourages nations to take three actions: enhancing international trade, streamlining procedures, and promoting transparency. Digital technology must be considered in the management of procedures if these three suggestions are to be implemented and directly impact the facilitation of international trade, especially regarding transit time and quality. Moreover, the World Customs Organization (WCO) has adopted coordinated border management (CBM) [WCO guide] as one of its tenets for the twenty-first century [2]. As a component of the global supply chain, the port area is dealing with the global digital transformation. The competitive role of global digital transformation contributes to the port area's rise to prominence in the supply chain. In this case, the demands of the port authorities force a modernization of ports that guarantees access to port services under equitable terms and with continuous availability, while also controlling transit costs and quality of service. In [1] unloading time for import containers is one of the criteria used to assess the efficiency of the container terminal, as the main benchmark in the port. The waiting time corresponds to the period during which an import container remains in a sea terminal (terminal waiting time) or a rail terminal (rail waiting time) before leaving on its journey within the country [2]. Container unloading time is therefore the time between when the containers are removed from the ship and when they take up a place in the port terminal. Prolonged unloading

in a port can have harmful consequences. According to [3], the operational costs of ports will be directly impacted by the delay in unloading containers, leading to increased inventory levels and allocation uncertainty. On the other hand, unloading time has been identified as an element of port competitiveness and a factor in port choice decisions [2], [4], [5]. Moreover, shippers consider that reducing dwell time and unloading time in ports in particular is one of the major objectives of the port supply chain [6]. As dwell time has a significant impact on port efficiency, research is needed to reduce it. Dwell time is determined by several variables, including insufficient port capacity, inadequate navigational aids, vessel consolidation, restricted cargo handling facilities, excessive equipment downtime, low worker productivity, and lack of storage space [7]. The technological element of terminal equipment, such as trucks and cranes, is also linked to dwell time [4]. Optimizing the dwell time of import containers will be the main focus of this modeling study.

The Port of Casablanca is the second-largest port in Morocco, following Tangier Med, and is strategically situated along the Atlantic coast. Established in 1912, the port has played a significant role in shaping Morocco's maritime trade and economic growth. Serving as a critical naval hub, the port handles a substantial portion of Morocco's container traffic. In 2022, it managed 1.7 million TEUs (Twenty-Foot Equivalent Units), with operations divided between two key container terminals. Container Terminal 1 (TC1), managed by Marsa Maroc, handled 700,000 TEUs, while Container Terminal 2 (TC2), [8] operated by Somaport, managed the remaining 1,000,000 TEUs. The primary function of a container terminal is to facilitate the unloading of containers from ships and their subsequent transport overland. Upon arrival at the port, import containers must be efficiently unloaded from the ship at the designated container terminal [8]. This process is crucial for maintaining the flow of goods and ensuring timely distribution to their next destinations, either by road or rail. Port terminal capacity is a key indicator of a port's performance and efficiency. It is defined as the total amount of cargo that the terminal can handle within a specific timeframe [9]. The capacity of a terminal is influenced by several factors, including the type and number of cranes, the operational efficiency of the terminal, and the storage capacity available at the shipyard. The estimation of the number of containers that can be stacked at a terminal is based on several variables, most notably container dwell times and the shipyard's storage capacity [10]. Container dwell time, in particular, is a critical metric that impacts yard congestion and overall terminal efficiency. It refers to the time taken to remove containers from a ship, measured from the moment the ship arrives at the port until the containers leave the port's premises. Container dwell time is a vital aspect of port operations [9], as it directly affects the throughput and capacity of the terminal. Prolonged dwell times can lead to congestion, reduced terminal capacity, and delays in the supply chain. Efficient management of container dwell times is therefore essential to ensure a smooth flow of goods and optimize terminal operations [10]. At container ports, integrating cutting-edge scheduling algorithms and optimization strategies can greatly increase handling capacity and decrease dwell times. Reducing container stay times and streamlining crane scheduling are two of the Port of Casablanca's operating difficulties. Effective scheduling techniques that can take into account the dynamic nature of container arrivals and departures are required due to the difficulty of managing multiple cranes (both gantry and mobile cranes) [11]. By increasing scheduling efficiency and decreasing turnaround times [12], the application of mathematical models and optimization methods, including genetic algorithms [13], has shown promise in tackling these issues. Port operations could be greatly improved by optimization approaches, particularly those based on evolutionary algorithms like genetic algorithms [14] by simulating the scheduling issue.

2. METHOD

2.1. Description of problem

A container ship consists of a set of bays. Each bay contains several containers. The unloading operation will be done by one quay crane (gantry) and one mobile crane knowing that each crane has a different unloading speed [15]. It is assumed that a gantry crane can handle 20 C/H (container/hour) and a mobile crane can handle 10 C/H, so the unloading time of a single container will be 3 and 6 (min) respectively. The problem is affecting the two cranes to bays to achieve a minimum unloading time. Both cranes work simultaneously, [16] so our objective is to balance the unloading time between the two cranes Table 1. For 2 cranes and 4 bays; the following graph illustrates the problem in question as shown in Figure 1. The unloading possibilities for each crane are presented in Table 1.

Table 1. Unloading possibilities for each crane

Bays	Cranes
One bay	1, 2, 3 or 4
Two Bay	1+2, 1+3, 1+4, 2+3, 2+4 or 3+4
Three bays	1+2+3, 2+3+4, 3+4+1 or 1+2+4

Assumptions: There is only one cargo ship taken into account. There are (n) bays in total. There are several containers in each bay. Every bay is unloaded by a single crane, and each crane can only go to the next after completing the preceding bay's unloading. The duration of two cranes' journey is not factored in.

Mathematical formulation data:

- i: bay index $\forall i=1, \dots, n$
- Mi: number of containers in each bay.
- Ut1: unloading time of one container by quay crane.
- Ut2: unloading time of a container by mobile crane.

Decision variables:

- $Z_i \in \{0, 1\}$ =1: if the bay can be unloaded by quay crane.
0: otherwise.
- $W_i \in \{0, 1\}$ =1: if the bay can be unloaded by mobile crane.
0: otherwise.

The objective function:

$$\text{Min}(f) = |Ut1 \sum Z_i M_i - Ut2 \sum W_i M_i| \quad (1)$$

Constraint:

$$Z_i + W_i = 1 \quad \forall i=1, \dots, n \quad (2)$$

The objective function is to minimize the difference between the times taken to unload the bays by the two cranes (1). Each bay must be unloaded by only one crane (2).

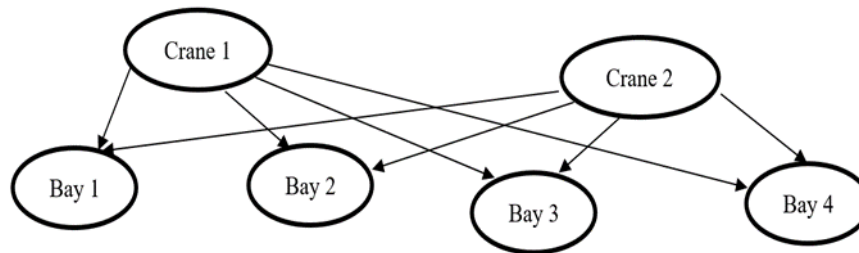


Figure 1. Presentation of the problem by a graph

2.2. Genetic algorithm

In this study, I use a genetic algorithm to determine the optimal crane assignment for large instances, especially when the number of containers to be unloaded is high. The genetic algorithm is particularly well-suited for this type of complex problem due to its ability to efficiently explore a vast solution space [17]. The exact method based on mixed-integer linear programming (MILP) provides optimal results for small instances with a limited number of containers [18]. However, this method quickly becomes ineffective and stalls when applied to large instances, due to the combinatorial explosion of the number of variables and constraints to be considered. By using the genetic algorithm, it is possible to overcome these limitations by generating near-optimal solutions [19] while reducing computation time, allowing for efficient crane assignments and improved planning of port operations. Genetic algorithm steps:

- The selection operator: Selection consists of choosing the best-adapted individuals to have a solution population that is closest to converging towards the global optimum.
- The crossover operator: Crossover is a genetic operator allowing children to inherit part of the first parent and part of the second parent.
- The mutation operator: The mutation operator is applied to individuals with a low probability [20]. Mutation consists of modifying the value(s) of one or more randomly selected genes of an individual. This operator favors diversification in the evolution of individuals [21].

3. RESULTS AND DISCUSSION

Two approaches are used in this paper to tackle the problem: an exact method using linear programming solved with Lingo, and a metaheuristic method using a genetic algorithm implemented in Python to solve the mixed-integer programming problem.

3.1. Linear programming solved with Lingo

In this section, we present a numerical example to illustrate the application of linear programming [22] for determining the optimal assignment of cranes at the quay, specifically focusing on selecting the appropriate type of crane. The problem involves a set of containers to be unloaded, each requiring a specific crane type in Table 2 based on container size, weight, and handling requirements. Using linear programming, we aim to allocate either gantry cranes or mobile cranes to maximize unloading efficiency while minimizing total operation time. The model considers several constraints, such as crane availability, [23] operational capacity, and the handling characteristics of the containers. By solving this optimization problem with Lingo, we determine the best crane assignment for each unloading task, ensuring an efficient schedule and improved utilization of quay resources. The results of this numerical example provide insights into the effectiveness in Table 3 of the proposed approach in achieving an optimal crane allocation strategy.

Number of bays :3

Number of containers in each bay :15, 10,18

Ut1 and Ut2: 2 and 4 min

FUT: final unloading time

With 2 cranes [1= quay crane, 2= mobile crane] we get 2^3 possibilities (8P).

Table 2. Possibilities for 2 cranes and 3 bay

	P1	P2	P3	P4	P5	P6	P7	P8
Z1	1	1	0	0	1	0	1	0
Z2	0	1	0	1	0	1	1	0
Z3	0	0	1	1	1	0	1	0
W1	0	0	1	1	0	1	0	1
W2	1	0	1	0	1	0	0	1
W3	1	1	0	0	0	1	0	1

Table 3. Final unloading time for each possibility

P	Crane 1 (min)	Crane 2 (min)	Min (f)	FUT (min)
122	$2*15=30$	$4*(10+18)=112$	82	112
112	$2*(15+10)=50$	$4*18=72$	22	72
221	$2*18=36$	$4*(15+10)=100$	64	100
211	$2*(10+18)=56$	$4*15=60$	4	60
121	$2*(15+18)=66$	$4*10=40$	26	66
212	$2*10=20$	$4*(15+18)=132$	112	132
111	$2*(15+10+18)=86$	0	86	86
222	0	$4*(15+10+18)=172$	172	172

The optimal solution is: Min (f) =4(min) and final unloading time =60 min

The optimal crane assignment that minimizes unloading time is identified as 211, meaning one mobile crane and two quay cranes. This combination efficiently handles the container load while reducing total operational time. The selection balances crane availability and capacity, ensuring streamlined operations at the quay.

3.2. Genetic algorithm

Genetic algorithm are based on three optimization strategies selection [24], mutation, and crossing that are drawn from natural evolution and genetic science [25]. As a result, while discussing genetic algorithms, the term "environment" refers to the search space, which is the set of possible parameter configurations for the function that needs to be optimized. In this context, a single person stands in for a possible configuration of the parameters [8]. A population is a collection of individuals. Every human can be represented by a chromosome, which is a line of genes that carries their unique genetic features [11]. A gene is the fundamental building block of a chromosome that codes for an attribute or function.

Example of our problem

1= gantry crane 2= mobile crane Bays: B1...B8 Parent X

B1	B2	B3	B4	B5	B6	B7	B8
1	1	1	2	1	2	2	2

Parent Y

B1	B2	B3	B4	B5	B6	B7	B8
1	2	2	2	1	1	2	1

One-point crossover

1	1	1	2	1	2	2	2
1	2	2	2	1	1	2	1

Two children

1	1	1	2	1	1	2	1
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1	2	2	2	1	2	2	2
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Mutation

Random position

1		1	2	1	1		1
1		1	2	1	1		1

3.3. Lingo solver result

A software program called LINGO is made to create and solve integer, nonlinear, and linear optimization models quickly and effectively. We have addressed the issue by developing a straightforward language model. There are three to nine different numbers of bays. There are 36, 42, 38, 44, 35, 32, 40, 44, and 39 containers in each berth. There are 36, 42, and 38 containers in each of the three berths. There are 36, 42, 38, 44, and 35 containers in each of the five berths. The findings are displayed in Table 4.

Table 4. Lingo solver results

Zi	Wi	Zi	Wi	Zi	Wi	Zi	Wi	Zi	Wi	Zi	Wi	Zi	Wi
1	0	1	0	0	1	1	0	1	0	0	1	1	0
1	0	1	0	1	0	1	0	0	1	1	0	1	0
0	1	1	0	1	0	1	0	1	0	1	0	0	1
		0	1	1	0	0	1	0	1	1	0	1	0
3Bay f=6				0	1	1	0	1	0	0	1	1	0
		4 Bays f=10						1	0	0	1	1	0
				5Bay f=30				1	0	1	0	0	1
						6 Bays f=50				1	0	1	0
								7Bay F66				0	1
										8 Bays f=83			
												9 Bays f=90	

3.4. Genetic algorithm result

Version 2.7 of Python is used to code the genetic algorithm. Python is a high-level, interpreted, object-oriented language with dynamic semantics. The genetic algorithm has been organized as follows:

- The generation of individuals is random.
- The fitness function=Min (f)
- One-point crossover.
- Mutation is random.
- Population of 100 individuals, and number of iterations :400.

The results of the genetic algorithm are presented in the Table 5.

$$\text{Ecart (Exact/AN)} = (\text{Makespan (AN)Makespan (Exact Method)} - \text{Makespan (AN)}) \times 100$$

- Makespan (Exact Method): The total completion time is calculated using the exact method.

- Makespan (AN): The total completion time calculated using the genetic algorithm).
- Difference: The formula subtracts the makespan of the genetic algorithm from that of the exact method.
- Interpretation Table 6: the result is positive; it indicates that the exact method has a longer makespan (worse performance) compared to the alternative method.

Table 5. Genetic algorithm results

Number of bays	Crane 1(min)	Crane 2 (min)	$f(min)$	Crane order
3	234	228	6	[1, 1, 2]
4	348	264	10	[1, 1, 1, 2]
5	372	426	22	[2, 1, 1, 1, 2]
6	453	456	32	[1, 1, 1, 2, 1, 2]
7	543	516	54	[1, 2, 1, 2, 1, 1, 1]
8	624	618	63	[2, 1, 1, 1, 2, 2, 1, 1]
9	699	702	74	[1, 1, 2, 1, 1, 1, 2, 1, 2]

Table 6. Comparison between the exact method and the genetic algorithm

Number if bays	Exact method	Genetic algorithm	Ecart (%)
3	6	6	0
4	10	10	0
5	30	22	0.36
6	50	32	0.56
7	66	54	0.22
8	83	63	0.31
9	90	74	0.21
7	66	54	0.22

4. DISCUSSIONS

As seen in Tables 4 and 5, the genetic algorithm enables us to identify the best crane assignment solution in large cases, especially when working with many bays. The genetic algorithm effectively manages larger-scale processes, as seen by scenario 4, where the objective value (f) of the exact technique is higher than that of the genetic algorithm. Its adaptability and ability to investigate a large solution space make it a strong option for crane allocation optimization, particularly when computational constraints make standard exact approaches unfeasible.

The genetic algorithm and the LINGO solver yielded identical results for small instances, with an execution time of less than 1(s) for the genetic algorithm and 2.86(s), 1.64(s), 1.14(s), 0.45(s), 0.14(s), 0.12(s), and 0.8(s) for LINGO. The outcomes of the genetic algorithm are recorded after three or four runs, and occasionally, as long as the cranes have unrestricted movement, the same solution (value of f) can take on multiple assignments. The gantry crane was able to accommodate a larger number of bays than the mobile crane in each example, ranging from three to nine bays. The quantity of containers in each bay and the pace at which each crane unloads have an impact on the effect of bays on the crane.

5. CONCLUSION

In this study, we tackled the crane scheduling problem at the container terminal of the Port of Casablanca, which is equipped with two gantry cranes and two mobile cranes. Our approach treated each bay as a distinct task that can be executed by either the gantry crane or the mobile crane, but never by both simultaneously. This simplification allowed us to establish a single constraint, streamlining the problem-solving process and making the model more manageable. However, there are several avenues for further research and improvement. Firstly, we could explore a scheduling model that involves only gantry cranes while incorporating an additional constraint to prevent interference between the cranes. This approach would allow for safer and more coordinated operations, reducing potential delays. Secondly, an alternative scheduling strategy could be developed where multiple cranes are permitted to unload each bay sequentially, but not concurrently. This method would take advantage of the combined capabilities of both gantry and mobile cranes, potentially yielding more efficient results by minimizing idle times and maximizing crane utilization.

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Aidi Sanaa	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
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C : **C**onceptualization

M : **M**ethodology

So : **S**oftware

Va : **V**alidation

Fo : **F**ormal analysis

I : **I**nterpretation

R : **R**esources

D : **D**ata Curation

O : **O**riginal Draft

E : **E**ditors

Vi : **V**isualization

Su : **S**upervision

P : **P**roject administration

Fu : **F**unding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The data that support the findings of this study are available from the port of Casablanca in Morocco.

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